Evaluating Cattle Manure Application Strategies on Phosphorus and Nitrogen Losses from a Florida Spodosol

A. K. Obour, M. L. Silveira,* J. M. B. Vendramini, M. B. Adjei, and Lynn E. Sollenberger

ABSTRACT

Repeated application of cattle (*Bos taurus*) manure to agricultural areas often results in soil P accumulation, which may pose risks to surface waters. We evaluated seven different application strategies on P and N losses from an established bahiagrass (*Paspalum notatum* Flügge) pasture: control (no N applied); two N sources [manure alone or manure plus ammonium nitrate (AN) (50/50% combination)]; two application frequencies (single or split); and two N rates (200 and 400 kg N ha^{-1}). Shallow groundwater P was monitored using piezometers installed at 60 cm (shallow wells) and 120 cm (deep wells). Surface runoff collectors were used to monitor runoff N and P from naturally occurring rainfall events. Soil samples were analyzed for Mehlich-1 P and KCl-extractable NH_4–N and NO_3–N concentrations. Application of manure in combination with AN suppressed leachate P, but no effect was observed on leachate NO_3–N concentrations in the shallow wells. Application of manure alone or in combination with AN did not affect P and N concentrations in the deep wells. Applying manure plus AN resulted in approximately 50% reduction in runoff N and P loads than treatments receiving manure alone. Manure applied alone or in combination with AN increased soil test P in upper soil horizons relative to control plots. Conversely, application of either manure or manure plus AN had no effect on soil NH_4–N and NO_3–N concentrations. Results demonstrate that combining manure application with inorganic N fertilizer represents an environmentally sound application strategy to reduce soil P and N accumulation and subsequent risks of nutrient transport.

In the United States and other developed countries, long-term application of manure to agricultural areas has been identified as a major contributing factor to water pollution (Sharpley et al., 2001; Withers et al., 2001; Kleinman et al., 2002; USEPA, 2002; Toor et al., 2003). In Florida, it is estimated that approximately 9.5 million kg of cattle manure are generated daily containing approximately 5.0×10^5 kg N, 1.0×10^5 kg P, and 3.0×10^5 kg K. Research in Florida has shown that beef ranches and dairy farms in the Lake Okeechobee Basin are the major contributors of P to the lake (Fonyo and Flaig, 1995). Thus, there is a need for management alternative strategies that result in optimal forage production and yet reduce losses to the environment following land application of manure.

Managing animal manure application to land is more complex than traditional inorganic fertilizer application because the nutrient concentration of manures is extremely variable, and not all nutrients are available immediately for plant uptake. Manure management strategies that synchronize amount of manure mineralization and crop demand results in greater manure utilization by plants and limits losses of nutrients to the environment (Harmel et al., 2009). Manure application rates traditionally have been based on crop N demand, a practice that typically results in soil P concentrations in excess of crop demand (Sims and Wolf, 1994; Eghball, 2002; Eghball et al., 2004). Although manure application based on crop P requirements may reduce excess P accumulation in the soil, it also results in substantially smaller manure application rates, larger land area required for manure disposal, higher cost associate with transport of waste outside sensitive watersheds, and N deficiency unless an additional supply of N is provided (Elliott et al., 2002).

Suitable N-based manure management, considering the balance between soil nutrient status, crop yields, and environmental impacts may provide a more efficient way of manure management in forage production systems. Application of manure in combination with inorganic N fertilizer is an alternative that can reduce P loads and improve the balance between N and P in the manure and that required by the crops. Evers (2002) observed that the combination of broiler litter and commercial N fertilizer increased P removal in an annual ryegrass (*Lolium multiflorum* L.)-bermudagrass [*Cynodon dactylon* (L.) Pers.] pasture. Moreover, addition of inorganic N fertilizer also may provide readily available N that can promote crop yields and P uptake rates (Obour et al., 2009). Although applying manure to established perennial pastures in combination with inorganic N can be a sound management strategy, there are limited data about the potential impacts on water quality.

The objectives of this study were to (i) investigate the impacts of different manure application strategies on soil test P and residual N concentrations and (ii) evaluate the effects of applica-

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Abbreviations: AN, ammonium nitrate; ICP–OES, inductively coupled plasma–optical emission spectrometry; M1-Al, Mehlich-1 extractable aluminum; M1-Fe, Mehlich-1 extractable iron; M1-P, Mehlich-1 extractable phosphrous; OM, organic matter; PSR, phosphorus saturation ratio; TDP, total dissolved phosphorus; TP, total phosphorus.

Table 1. Chemical characteristics of cattle manure applied in 2005 and 2006.

Application date		pH	Moisture content	Total			NH_4–N
Year	Month			N	P	K	
				g kg^{-1} dry matter			
2005	July	8.2	636	18	4	18	1.3
	September	8.6	711	25	7	25	2.0
2006	March	8.4	762	20	5	29	1.6
	August	8.7	735	21	6	20	1.7

tion of manure alone or in combination with AN on subsurface leaching and runoff of P and N from bahiagrass swards.

MATERIALS AND METHODS

The experiment was conducted in 2005 and 2006 on an established bahiagrass field at the University of Florida Range Cattle Research and Education Center at Ona, FL (27°26′ N, 82°55′ W) on an EauGallie sand (sandy, siliceous, hyperthermic Alfic Alaquod). The soil consisted of a very deep, poorly drained spodosol with moderate to slow permeability. The experimental site had no history of N and P fertilization during the past 15 yr. The treatments consisted of a control (no N application), two N sources (cattle manure alone and in combination with AN), two N rates (200 and 400 kg N ha^{-1}), and two application frequencies (single or split). Plot size was 6 by 6 m with a 3-m alley between plots.

Manure used for the study was collected from the cow pen of the UF/IFAS Range Cattle Research and Education Center in Ona, FL. The beef cattle fed mainly on grazed bahiagrass pasture with very little mineral supplementation. Animals were brought to the pens for routine medication where they usually stayed 3 to 5 d. Manure, which included feces and urine, was scraped from the concrete floor and stored outside the pen until application. Manure was sampled before each application and analyzed for pH, total Kjeldahl N (TKN), P, K, and NH_4–N concentrations (Table 1) at the UF/IFAS Livestock Waste Testing Laboratory at Suwannee Valley, FL. At each sampling, six random samples were taken from the manure pile and stored at 4°C until analysis.

In 2005, treatments were applied in July due to delay in plot preparations, therefore treatments that received split (50/50) application of manure and manure plus AN were fertilized in July and September. In 2006, treatments were applied in March, and split-applied treatments were fertilized in March and August. Fresh manure was weighed in buckets, manually applied on the plots and uniformly spread with the aid of a rake. Manure application rates were calculated based on total N concentration of the manure. The 200 kg N ha^{-1} application rate was intended to simulate N amounts recommended for manure application in bahiagrass pastures (Mylavarapu et al., 2007), whereas the 400 kg N ha^{-1} represented twice the recommended N rate. In 2005, manure was applied at 0, 30, and 60 Mg ha^{-1} for the treatments that received manure alone, which corresponded to N rates of 0, 200, and 400 kg N ha^{-1}, respectively. In 2006, the same treatments received 0, 42, and 84 Mg $ha^{-1}$of manure. The amounts of P applied with the manure were approximately 0, 52, and 104 kg P ha^{-1} for the 0, 200, and 400 kg N ha^{-1} treatments, respectively. Manure plus AN treatments received half of the manure and P rates applied in each year.

Surface and Groundwater Monitoring

To monitor water quality effectively in each treatment, plots were bermed into isolated hydrological units. Berming was done by digging a 120-cm deep ditch along the perimeter of each plot using a chain-driven ditching apparatus and burying a 5-mm plastic sheet to a 120-cm soil depth. The plastic sheets were supported 30 cm above the soil level with metallic berms placed to contain runoff within the plot. This procedure was done to prevent lateral flow of water between plots as the spodic (Bh) horizon at the experimental site typically is at a depth of 105 cm.

Two piezometers were installed in the center of each plot at 60- and 120-cm depths just above or below the spodic horizon, respectively. The piezometers consisted of a PVC well (0.05-m internal diameter) that was screened in the bottom 0.20 m. Water samples were collected by pumping water slowly from the piezometers using the method of prolonged slow pumping at a steady rate (Backhus et al., 1993). A mini-suction lift pump was used to collect groundwater samples. Approximately 250 mL of water were pumped directly into a glass container. Leachate samples were collected from the piezometers immediately after rainfall events >15 mm (when samples were available). In both years, leaching events generally occurred 30 to 60 d after manure application.

Leachate samples were collected within 2 to 24 h (depending on the soil water conditions), and subsamples were acidified with a drop of concentrated H_2SO_4 and stored at 4°C until analysis. Water samples were analyzed for total dissolved phosphorus (TDP), total phosphorus (TP), and NO_3–N concentrations. Total P was determined by inductively coupled plasma–optical emission spectrometry (ICP–OES) after persulfate digestion (USEPA, 1993). Total dissolved P also was analyzed using the ICP–OES after filtering the samples through a 0.45-μm Millipore. Nitrate-N was analyzed on a Seal AQ_2 discrete auto analyzer (Seal Analytical Inc., Mequon WI) using USEPA Method 353.2 (USEPA, 1993).

Surface runoff collectors measured approximately 30 by 80 cm and consisted of a stainless steel apparatus with two sets of sample splitters and two collection ports (1/10 and 1/100 of the total runoff flow) (Fig. 1). The samplers were installed at the lowest elevation of each plot by embedding the collector frame into the soil until the apparatus was parallel to the soil surface. The flow splitters diverted a fraction of the total runoff so the sample collected represented 1/10 (0.1x) or 1/100 (0.01x) of the total runoff flow. In this study, runoff water samples were collected from the 10x collection port. Samples from the runoff collector were routed by 2-cm plastic tube to 8-L containers buried below the soil surface.

Runoff volume was measured volumetrically immediately after major (>15 mm) rainfall events and subsamples (~250 mL) collected and stored at 4°C before laboratory analysis. Cumulative runoff volume for each treatment was calculated by summing the runoff (mm) of each sampling event and multiplying by 10 (proportion of the runoff volume collected by the runoff collector). Cumulative runoff N and P loads (g ha^{-1}) were calculated by dividing the total mass (g) in the runoff water by the plot area (0.0012 ha). A total of four naturally occurring runoff events occurred in 2005 during the months of August, September, October, and November. The first runoff event in 2005 occurred ~ 30 d after treatment application, which may have reduced runoff P and N potential due to extended time between the manure application and runoff-generating rainfall. In 2006,

treatment application occurred in March; however because of limited rainfall no runoff samples were collected this year.

Runoff volume and TDP, TP, and NO_3–N concentrations were used to calculate flow-weighted runoff concentrations as follows:

$$\text{Flow-weighted concentration (mg L}^{-1}\text{)} = \text{runoff volume (L)} \times \text{concentration (mg L}^{-1}\text{)} / \text{cumulative runoff volume (L)}$$

Soil Analysis

Ten 5-cm composite soil core samples were taken from the 0- to 15-, 15- to 60-, and 60- to 120-cm soil depths using a 5-cm diam. core sampler. These depths represent the Ap, E, and Bh horizons, respectively. Soil samples were collected at the initiation of the study and after each growing season in November 2005 and 2006. Soil samples were air-dried, crushed, and sieved to pass through a 2-mm stainless steel screen and analyzed using the standard soil testing procedure of the University of Florida-Extension Soil Testing Laboratory (Mylavarapu, 2002). Subsamples used for determination of soil extractable NO_3–N and NH_4–N concentrations were stored at 4°C until analysis. Mehlich-1 extractable P, Al, and Fe were measured using 5 g of soil and 20 mL of Mehlich-1 extracting solution (0.0125 M H_2SO_4 + 0.05 M HCl) (Mehlich, 1953). The mixture was shaken for 5 min in a reciprocating shaker and filtered through Whatman no. 42 filter paper. Extracted elements were analyzed using ICP–OES. Soil pH was determined using 1:2 (weight/volume) soil/deionized water with a glass electrode. Soil organic matter (OM) was determined by loss on ignition (Nelson and Sommers, 1982). Soil extractable NO_3–N and NH_4–N concentrations in the Ap horizon were determined using 2 g of soil and 20 mL of 2 M KCl solution (Mulvaney, 1996). Nitrate-N and NH_4–N in the extracts were analyzed on a Seal AQ_2 discrete auto analyzer (Seal Analytical Inc., Mequon WI) using USEPA Method 353.2 (USEPA, 1993). Phosphorus saturation ratio (PSR), a degree to which P sorption capacity of a soil has been saturated, was calculated according to Eq. [1] (Nair et al., 2004).

$$\text{PSR} = \text{M1-P}/(\text{M1-Al} + \text{M1-Fe})$$

where M1-P, M1-Al, and M1-Fe correspond to Mehlich-1 extractable phosphorus, aluminum, and iron concentrations, respectively, expressed in moles.

Statistical Analyses

Treatments were the factorial arrangement of two N rates, two sources, and two frequencies of application replicated three times in a randomized complete block design. Statistical analyses were performed using Proc GLM (General Linear Model procedure of SAS, SAS Institute, 1999). Nitrogen rates and sources and application frequencies were considered fixed effects, with replicates and their interactions considered as random effects. Mean separation was performed using the SAS least square means (LSMEANS) test (probability of difference [PDIFF]) at $P \leq 0.05$. Because the experiment consisted of an unbalanced experimental design, single degree of freedom orthogonal contrasts were used to compare the treatments vs. the control. Water data were log-transformed before analysis, if necessary, to normalize the data. Treatments and their interactions were considered different when F test P values were ≤0.05. Interactions not mentioned in the text were not significant ($P > 0.05$).

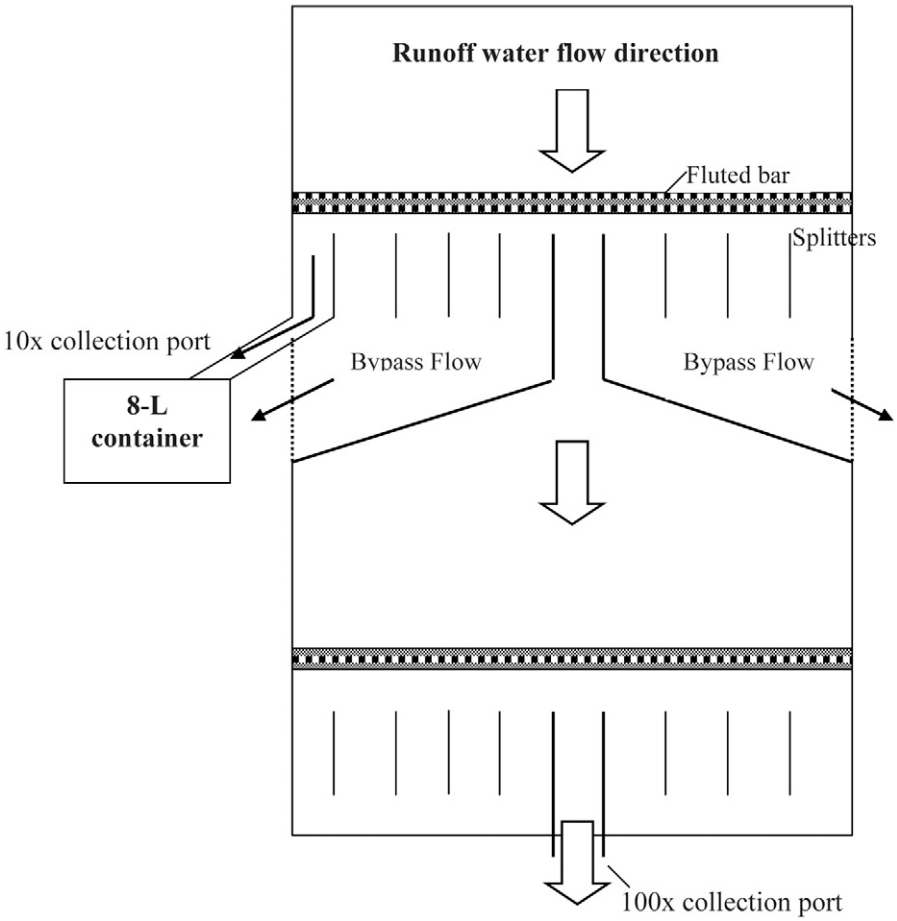

Fig. 1. Schematic representation of the runoff collectors.

RESULTS AND DISCUSSION

Climatological Data

Cumulative rainfall in 2005 was 1654 mm and 911 mm in 2006. In 2005, cumulative rainfall exceeded the 65-yr average by 282 mm. Rainfall in 2006 was approximately 460 mm below the 65-yr average. Excessive rainfall and high water table levels in 2005 prevented berming of plots until the end of June causing a delay in the initiation of the experiment. In 2005, treatments were applied in July, which corresponded to a period of intensive rainfall when the risk of runoff was greatest. Cumulative rainfall between May, which corresponded to the beginning of the growing season, and treatment application

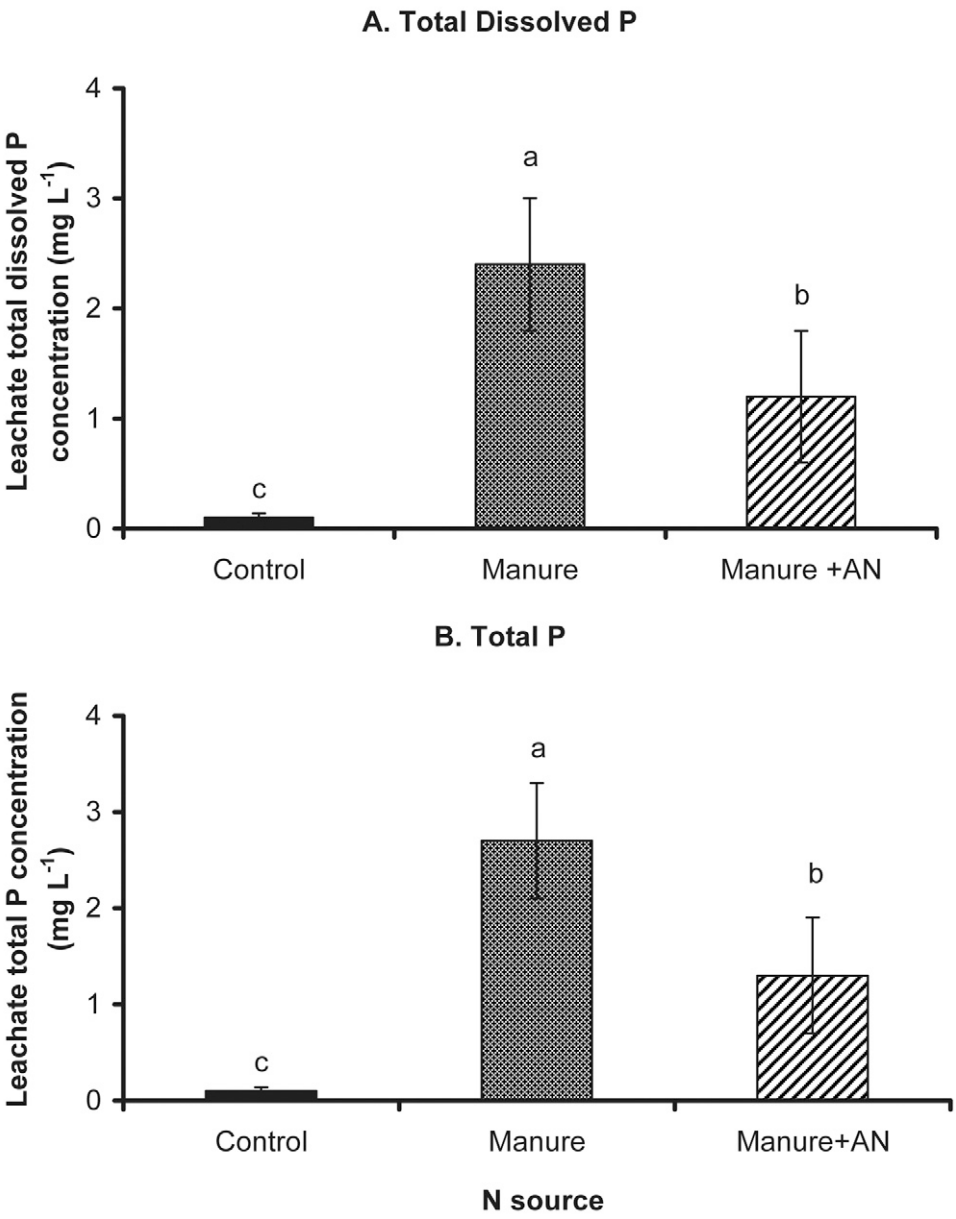

Fig. 2. Nitrogen source effect on (A) total dissolved P and (B) total P concentration in the shallow wells (60-cm depth) in 2005. Data are means across N rates and application frequency. Means followed by same letter within N source are not different using the LSMEANS/PDIFF procedure ($P > 0.05$). Error bars indicate one standard error.

in July 2005 exceeded the 65-yr average by 143 mm. Excessive rainfall during the summer months and timing of treatment application was expected to have important implications in terms of nutrient transport because a significant proportion of the yearly runoff is likely to occur during this period.

Average minimum (17°C) and maximum (28°C) temperatures were relatively similar in 2005 and 2006; hence, precipitation was likely the most important environmental factor limiting plant growth. More details about treatment effect and environmental conditions on crop yield response and nutrient uptake efficiency are presented in Obour et al. (2009).

Shallow Groundwater Phosphorus and Nitrogen Concentrations

Year showed no significant effects on leachate P and N concentrations in 2005 and 2006; therefore, average TP, TDP, and NO_3–N concentrations across the sampling events are presented. There were differences ($P \leq 0.001$) among N sources on TDP and TP concentrations in the shallow (60-cm depth) wells in 2005 (Fig. 2). Average TDP concentrations in 2005 were 0.09 for the control, and 1.2 and 2.4 mg L^{-1} for treatments that received manure plus AN and manure alone, respectively (Fig. 2a). In 2005, TP concentrations in the shallow well were 0.1 for the control, 1.3 mg L^{-1} for treatments that received manure plus AN, and 2.8 mg L^{-1} for manure alone. There was no significant effect of manure application rate or application frequency on TDP and TP concentrations of shallow wells in 2005.

In 2006, there was interaction between N source and rate of application ($P = 0.001$) on leachate P. Increasing manure application rate increased TDP and TP concentration for each N source (Fig. 3). Total dissolved P concentration increased from 0.02 mg L^{-1} for the control, to 3.8 and 18.8 mg L^{-1} when manure alone was applied at rates of 200 and 400 kg N ha^{-1}, respectively. Application of manure plus AN at rates of 200 and

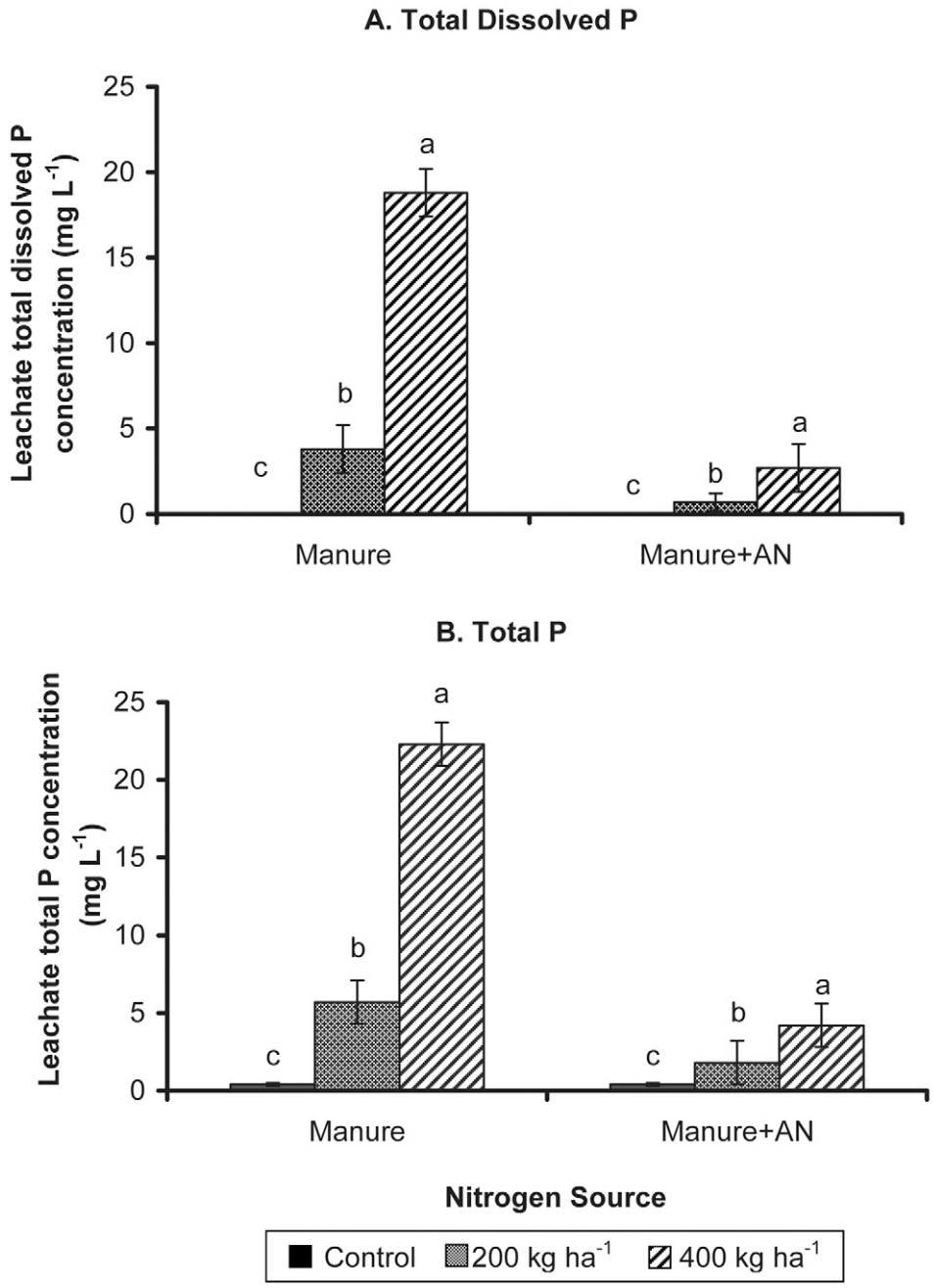

Fig. 3. Leachate (A) total dissolved P and (B) total P concentration in shallow wells (60-cm depth) as affected by N source and application rate in 2006. Data are averages across application frequency. Means followed by same letter within N source are not different using the LSMEANS/PDIFF procedure (*P* > 0.05). Error bars indicate one standard error.

400 kg N ha^{-1} rate resulted in TDP concentration of 0.7 and 2.7 mg L^{-1}, respectively (Fig. 3a). The combination of manure with AN resulted in ~83% reduction in the amount of TDP leached at either application rate. Similarly, TP in the leachate followed a similar trend as TDP. Total P concentration ranged from 0.4 mg L^{-1} for the control and 22.3 mg L^{-1} for the treatments that received manure alone at 400 kg N ha^{-1} (Fig. 3b). Leachate total P was also significantly lower in the manure plus AN treatments than in the treatments receiving manure alone.

Although control plots exhibited similar leachate P concentration in the shallow wells during the 2-yr study (0.1 mg P L^{-1}), leachate P concentrations increased in 2006 for the plots receiving manure alone or in combination with AN. Greater leachate P concentrations observed in the shallow wells in 2006 (average TP of 8.5 mg L^{-1}) compared to 2005 (average TP of 2.0 mg L^{-1}) indicated a detrimental effect of repeated manure application on water quality. Since coarse-textured Spodosols typically exhibit low P-sorbing capacity (Villapando and Graetz, 2001), application of either manure or manure plus AN resulted in substantial movement of P via subsurface leaching. This finding was further supported by the differences in soil P concentration at the various depths. Soil test P concentration in the E horizon, which correspond to the depth of the shallow well, was significantly higher in 2006 compared to the initial soil test P, suggesting P accumulation and subsequent leaching of P below the A horizon occurred in response to repeated manure applications.

Leachate samples in the shallow wells occurred only when water table was at or near the soil surface. In both years, the first leaching

Table 2. Runoff volume, mean flow-weighted concentrations, and cumulative loads of total phosphorus (TP), total dissolved phosphorus (TDP), and NO_3–N in runoff as affected by N source.

Treatment	Cumulative runoff volume	Concentration			Loads		
		TP	TDP	NO_3–N	TP	TDP	NO_3–N
	mm	mg L^{-1}			g ha^{-1}		
Control	22a†	0.2c	0.01c	0.1c	40c	21c	38c
Cattle manure	17a	5.6a	4.4a	1.9a	1086a	876a	209a
Cattle manure plus ammonium nitrate	19a	2.9b	2.0b	1.0b	380b	378b	74b

† Means followed by the same letter within column are not significantly different using the LSMEANS/PDIFF procedure ($P > 0.05$).

event collected from the shallow well occurred in September, which corresponded to a period of intensive precipitation in South Florida. Although the effects of fluctuating water table on P dynamics under field conditions is difficult to predict, our data suggest that P released from the Ap horizon likely flows vertically in the soil profile and is resorbed as Al-P or Fe-P compounds in the Bh horizon.

There were no treatment effects on TDP and TP concentrations in the deep wells (120-cm depth) over the 2-yr study period. It is likely that P leached into the deep wells was mixed with the groundwater, masking possible treatment effects. In 2006, leachate TP concentrations in the deep wells were 0.7 mg L^{-1} for the control, 1.8 mg L^{-1} for the manure plus AN treatments, and 2.9 mg L^{-1} for the manure alone treatments. Although leachate TP concentration was greater for the manure-alone plots compared to manure plus AN, no statistical differences were observed likely due to the high variability associated with TDP and TP in the deep wells. In addition, manure plus AN treatments received half the amount of P supplied to manure alone treatments, therefore smaller leachate P concentrations were expected.

Greater P concentrations were observed in shallow (60 cm) wells than in the deep (120 cm) wells and may indicate that limited P leaching is likely to occur below the Bh horizon. The lower TDP and TP concentrations in the deep wells compared to the shallow wells also reflect the differences in P-sorption capacities between the E and Bh horizons. The high P sorption capacity of the Bh likely reduced the amount of P released into solution, whereas P was easily transported in the E horizon because the low affinity and binding sites for P adsorption in this soil horizon. This result is consistent with soil test P concentrations in the Bh horizon that suggested that limited P was moved from the soil surface to deep (60–100-cm) soil depths. Our findings are also consistent with results of Villapando and Graetz (2001), who observed in a soil column study that the Bh horizon from a manure-impacted Florida Spodosol provides storage for P that moves vertically from overlying soil horizons.

Addition of N as either manure or manure plus AN had no effect ($P = 0.2$) on NO_3–N concentrations in the shallow and deep wells. Mean NO_3–N concentrations in the shallow wells were 0.05 mg L^{-1} for the control, 0.04 mg L^{-1} for the manure treatment, and 0.06 mg L^{-1} for the manure plus AN plots. This result was somewhat unexpected. We hypothesized that addition of inorganic fertilizer would likely increase nitrate leaching potential. However, our data showed that at the rates used in this study (200 and 400 kg N ha^{-1}), application of manure or manure plus AN has no impacts on leachate NO_3–N concentrations. Greater crop dry matter yields in response to N application (Obour et al., 2009) likely resulted in reduced availability of N to be lost via subsurface leaching. This finding is further supported by the soil residual N data that showed extractable NO_3–N concentrations were unaffected by treatment application.

Surface Runoff Phosphorus and Nitrogen

There were no significant differences among runoff sampling events in 2005 on runoff P and N concentrations ($P = 0.256$); therefore, average TP, TDP, and NO_3–N concentrations across the sampling events are presented. As might be expected for flatwood soils, the majority of the P transported via runoff was in dissolved form. The mean flow-weighted concentration of TP, TDP, and NO_3–N concentrations and cumulative loads were significantly affected ($P = 0.003$) by N sources (Table 2). Application of manure plus AN reduced TP, TDP, and NO_3–N concentrations in runoff by approximately 50% compared to the treatments that received manure alone. Similarly, mass loads of P and NO_3–N were reduced by as much as 64% if manure was applied in combination with AN compared to manure alone. No effect of treatment was observed with cumulative runoff volume ($P = 0.3$). Though treatments affected crop dry matter yield (Obour et al., 2009) and, therefore, could potentially affect ground cover, the number of runoff-producing events were similar among the treatments.

Compared to control plots, manure and manure plus AN treatments increased runoff TP, TDP, and NO_3–N concentrations. Despite the limitation in comparing runoff data from naturally occurring rainfall with other reports in the literature, runoff P concentrations observed in our study are consistent with Rechcigl et al. (1992), who evaluated P rates of 0 and 48 kg ha^{-1} (from triple superphosphate) applied to bahiagrass growing on a Spodosol. They reported runoff dissolved P concentrations of 0.42 mg L^{-1} with the 0 P treatment and 3.45 mg L^{-1} with the 48 kg P ha^{-1} treatment. Similar to your results, Capece et al. (2007) observed annual runoff P loads of 1.7 kg P ha^{-1} from bahiagrass pastures in south Florida.

The relatively extended period between treatment application and runoff-producing rain (~30 d) likely decreased runoff P and N. Numerous studies under simulated rainfall conditions have demonstrated that extending the timing between manure application and a runoff event can reduce the risk of runoff P (Westerman and Overcash, 1981; Sharpley, 1997; Hanrahan et al., 2009). In addition, the relatively lower runoff N and P concentrations reported here compared to rainfall simulation studies is likely due to differences in runoff response to natural occurring rainfall events. Differences in intensity and duration of rainfall events, soil properties, and moisture conditions are expected to have major impacts on runoff response to natural and simulated rainfall events.

Unlike other studies that showed effects of manure application rate on nutrient transport via runoff (Dougherty et al., 2008; Menjoulet et al., 2009), our results indicated that increasing manure rates from 200 to 400 kg N ha^{-1} had no impact on runoff P or N. This result may partially be due to the relatively low manure application rates associated with the extensive bahiagrass root system and dense ground cover which likely minimize

Table 3. Runoff volume and mean flow-weighted concentrations and cumulative loads of total phosphorus (TP), total dissolved phosphorus (TDP), and NO_3–N in runoff as affected by application frequency.

Treatment	Cumulative Runoff Volume	Concentration			Loads		
		TP	TDP	NO_3–N	TP	TDP	NO_3–N
	mm	mg L^{-1}			g ha^{-1}		
Split application	18a†	2.6b	2.2b	0.7a	319b	337b	111b
Single application	17a	5.3a	4.2a	1.1a	1145a	868a	172a

† Means followed by the same letter within column are not significantly different using the LSMEANS/PDIFF procedure ($P > 0.05$).

nutrient transport via runoff. Application frequency of either manure or manure plus AN affected runoff P ($P = 0.03$) and N loads ($P = 0.04$) (Table 3). Manure P and N were more susceptible to runoff losses when either manure or manure plus AN was applied once per year. Single application of either manure or manure plus AN treatments resulted in runoff TDP and TP concentrations approximately two times greater than split-applied treatments. Although runoff NO_3–N concentrations were not affected by application frequency, NO_3 load in runoff was reduced by split application of treatments. Reduced runoff P and N was likely due to increased bahiagrass yield and nutrient uptake efficiency when treatment were split applied compared to single application (Obour et al., 2009).

Numerous studies have shown that surface runoff may not be a major pathway for P loss in sandy soils of Florida because of the predominantly flat topography; subsurface leaching through lateral flow has been pointed as the preferential pathway for P transport (Burgoa et al., 1991; Campbell et al., 1995; Mansell et al., 1995). The relative small cumulative runoff volume (17–22 mm) measured in our study (Table 2) accounted for ~1% of cumulative precipitation in 2005, which may further indicate that infiltration rather than surface runoff is the predominant mechanism for nutrient transport. The small amount of runoff measure during the 2-yr study also confirmed that the risk associated with nutrient transport via runoff was likely low, especially given that only four runoff events were observed.

Residual Soil Test Phosphorus Concentrations and Phosphorus Saturation Ratio in the Ap, E, and Bh Horizons

Spodosols are the predominant soil order in south and central Florida. They typically pose a water table between the surface horizon (0–15 cm) and spodic horizon (50–60 cm) (Soil Survey Staff, 1996). In our study, subsurface horizons (E and Bh) were discontinuous and their depth varied (16–60 cm for E, 61–120 for Bh). Horizons ranged in organic matter concentration from 23 g kg^{-1} in the Ap horizon to 3 g kg^{-1} in the E horizon. Initial Mehlich 1-P concentrations in the Ap, E, and Bh horizons were 8.5, 1.5, and 54 mg kg^{-1}, respectively. Mehlich 1-Fe and-Al concentrations in the Ap horizon were 47 and 49 mg kg^{-1}, respectively, 6.5 and 11 mg kg^{-1} in the E horizon, and 75 and 511 mg kg^{-1} in the Bh horizon.

There was N source × application frequency × N application rate interaction ($P = 0.02$) effect on residual soil P concentration and PSR ($P = 0.03$) in Ap horizon after 2 yr of manure application. Applying manure and manure plus AN resulted in greater residual soil P concentration in the Ap horizon than in the control plots (Fig. 4). After 2 yr of manure application, soil residual P concentration in the Ap horizon ranged from 1.5 mg kg^{-1} for the control to 51 mg kg^{-1} when manure was applied once per year to provide 400 kg N ha^{-1}. However,

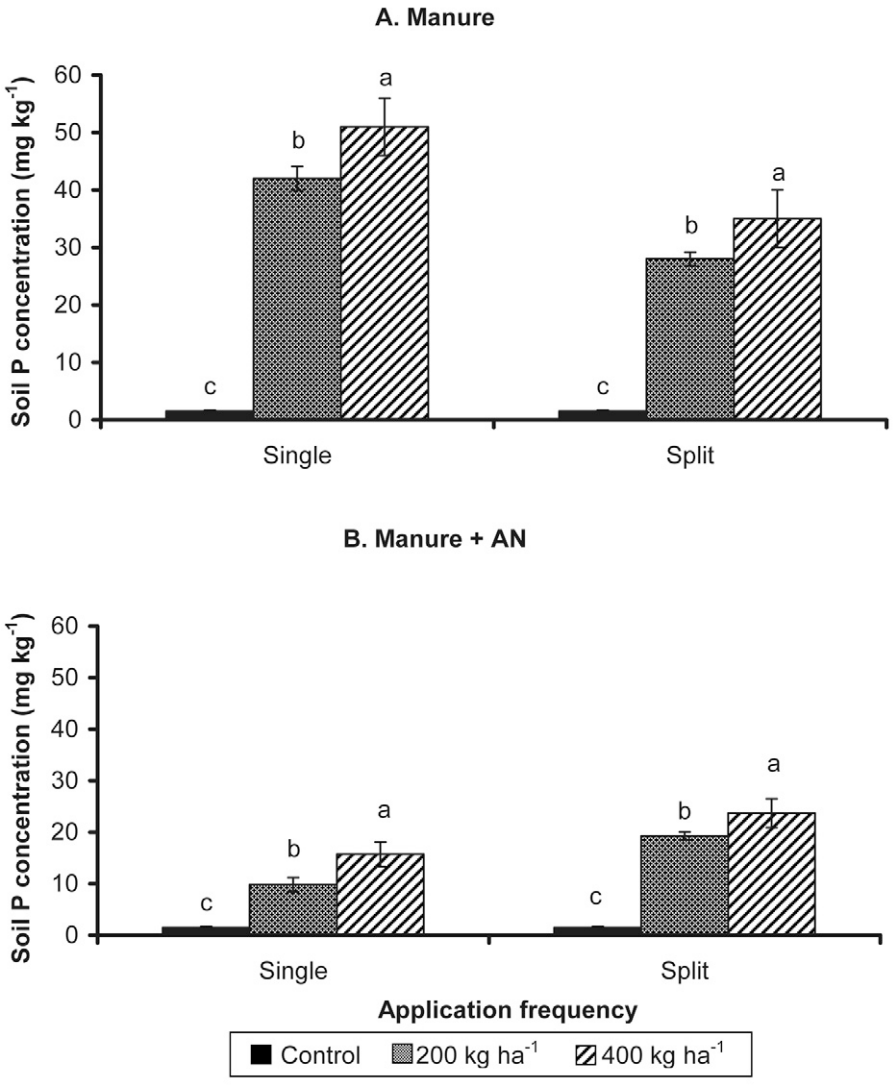

Fig. 4. Soil P concentration in the Ap horizon (0–15-cm depth) for the (A) manure and (B) manure + AN treatments as affected by N source, rate, and application frequency after 2 yr of manure application. Means followed by same letter within application frequency are not different using the LSMEANS/PDIFF procedure ($P > 0.05$). Error bars indicate one standard error.

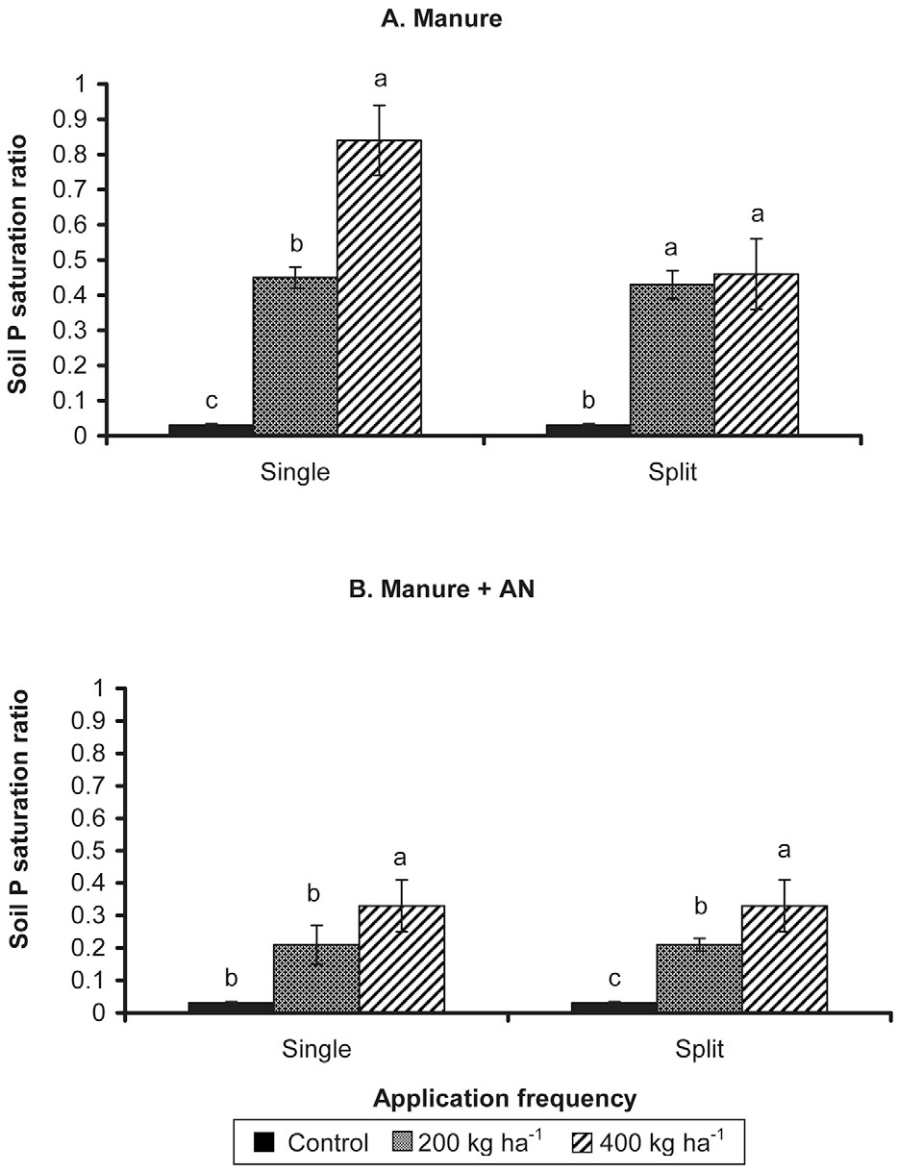

Fig. 5. Soil P saturation ratio in the Ap horizon (0–15-cm depth) for the (A) manure and (B) manure + AN treatments as affected by N source, rate, and application frequency after 2 yr of manure application. Means followed by same letter within application frequency are not different using the LSMEANS/PDIFF procedure ($P > 0.05$). Error bars indicate one standard error.

application of manure plus AN resulted in significant lower soil P concentrations compared to treatments that received only manure. In general, manure plus AN had less than half the residual soil P concentration in the Ap horizon than treatments that received manure alone. Using the current Mehlich 1 soil-test P interpretations in Florida (Mylavarapu et al., 2007), plots receiving 2 yr of manure application exhibited high soil-test P (31–60 mg kg^{-1}), while plots receiving manure plus AN were medium (16–30 mg kg^{-1}). Lower soil P concentration in the manure plus AN treatments occurred because they received half the P load of manure alone plots. In addition, greater bahiagrass yield of manure plus AN treatments compared to manure alone enhanced crop P recovery resulting in lower P accumulation in the soil (Obour et al., 2009). Our results indicated that applying manure alone has a greater potential to increase soil P buildup and, consequently, greater tendency of subsurface leaching or runoff of P compared to plots treated with manure plus AN.

Regardless of the N application rate, a single application of manure resulted in significantly greater residual Mehlich-1 soil P concentration in the Ap horizon than split application (Fig. 4a). Residual Mehlich-1 soil P concentration was 43 mg kg^{-1} when manure was applied once per year at 200 kg ha^{-1} compared to 28 mg kg^{-1} when the same treatment was split applied (Fig. 4a). In contrast, split applying manure plus AN resulted in significantly greater soil P concentration than when treatments were applied once per year (Fig. 4b). Soil P concentration in the Ap horizon averaged 9.8 mg kg^{-1} when manure plus AN was applied once per year at 200 kg N ha^{-1} and 19.3 mg kg^{-1} when the same treatment was split applied. Similarly, split application of manure plus AN at 400 kg N ha^{-1} resulted in soil P concentration in the Ap horizon of 24 mg kg^{-1} compared to 16 mg kg^{-1} when split applied (Fig. 4b).

As with soil test P, P saturation ratio in the Ap horizon was also greater for the manure alone treatments than with the treatments that received manure plus AN application (Fig. 5). After 2 yr of the study, PSR was 0.03 for the control and 0.82 for treatments that received 400 kg N ha^{-1} from manure applied once per year (Fig. 5a). Increasing N application rate via either manure or manure plus AN generally increased PSR. The only exception was the split-applied manure alone treatments, where no significant differences between the 200 and 400 kg N ha^{-1} rate were observed. Phosphorus saturation ratio was lower for the treatments receiving manure plus AN treatments compared to manure alone (Fig. 5b).

There was significant N source × application frequency × N rate interaction for soil P concentration in the E horizon. Soil P concentration ranged from 0.4 mg kg^{-1} for the control to 10 mg kg^{-1} when manure was applied at the 200 kg N ha^{-1} rate (Fig. 6a). Treatments that received manure plus AN had lower soil P concentration in the E horizon than the manure alone treatments. Soil P concentrations in the E horizon for the manure plus AN ranged from 1.1 mg kg^{-1} when applied once per year at 200 kg N ha^{-1} to 3.5 mg kg^{-1} when manure plus AN was applied once at 400 kg N ha^{-1}(Fig. 6b).

There was no treatment effect on soil P concentration ($P = 0.2$) and PSR ($P = 0.7$) in the Bh horizon. Residual soil P concentrations in the Bh horizon over the 2 yr were 18 mg kg^{-1} for the control, 21 mg kg^{-1} for manure plus AN treatments, and 29 mg kg^{-1} when manure was applied alone. The PSRs were 0.04, 0.05, and 0.06, respectively for the same treatments. The relatively high PSR observed in the Ap horizon compared to the Bh horizon indicated that there was little P leaching from the Ap into the Bh horizon

over the 2-yr study. This result may also be due to the differences in P sorption capacity between the two horizons. The Ap and E horizons of Spodosols in Florida have lower P sorption capacity than the Bh horizon (Mansell et al., 1992; Nair et al., 2004).

Changes in Soil Residual Nitrogen

There was no treatment effect on soil NH_4–N and NO_3–N concentrations during the 2-yr period. Mean soil extractable NH_4–N and NO_3–N concentrations in 2006 respectively were 12 and 0.09 mg kg^{-1} for the control, 14 and 0.1 mg kg^{-1} for the treatments receiving manure, and 13 and 0.1 mg kg^{-1} for manure plus AN treatments. Our results suggest that manure applied at agronomic rates has negligible effects on residual soil NH_4–N and NO_3–N concentrations over time. A significant proportion of applied N was taken up by the bahiagrass to sustain growth. In general, greater N application rates via manure or manure plus AN increased tissue N concentration and N accumulation (Obour et al., 2009), which result in minimum risks of N accumulation in the soil. Our findings conform with the concept that application of manure supplemented with AN improved the efficiency of manure N utilization likely because AN provided readily available N to stimulate bahiagrass growth, increased yield, and removal of more plant available N compared to manure supplied alone (Evers, 2002; Obour et al., 2009).

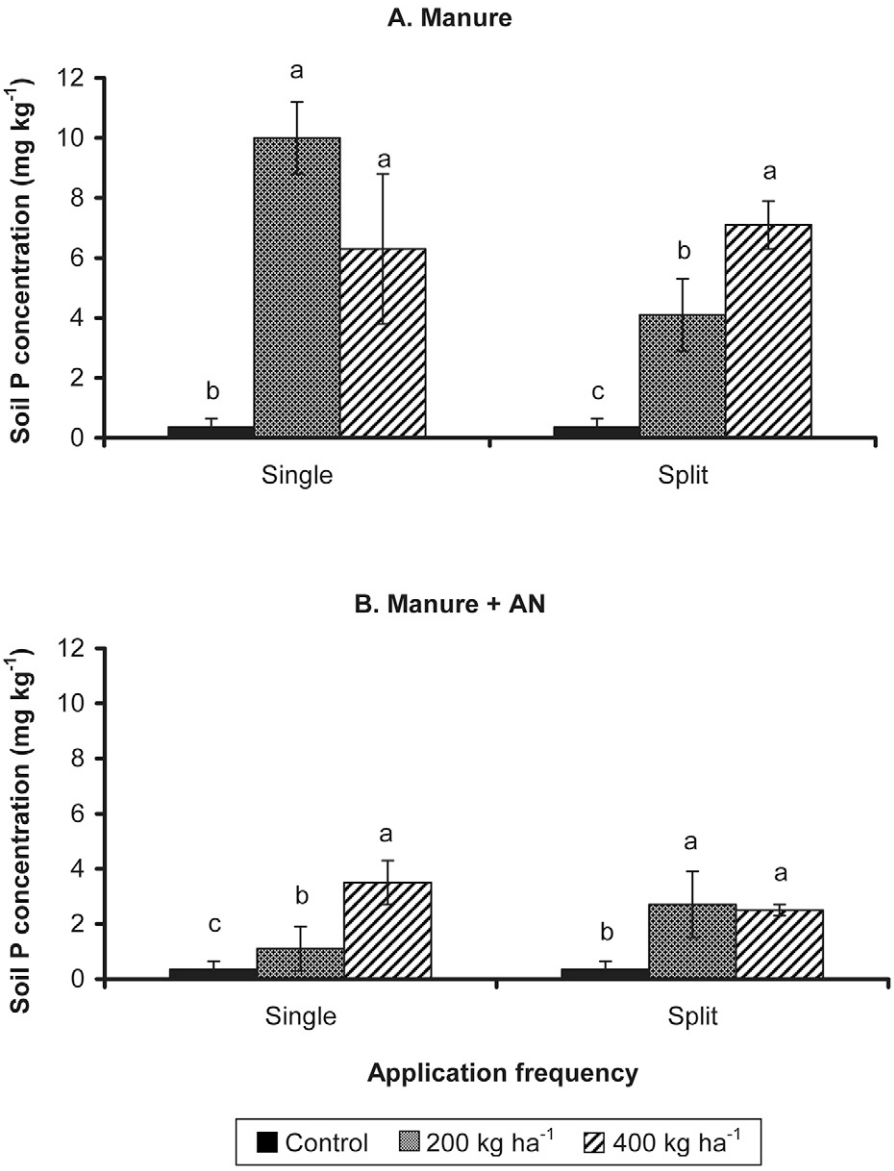

Fig. 6. Soil P concentration in the E horizon (15–60-cm depth) for the (A) manure and (B) manure + AN treatments as affected by N source, rate, and frequency of application after 2 yr of manure application. Means followed by same letter within application frequency are not different using the LSMEANS/PDIFF procedure (*P* > 0.05). Error bars indicate one standard error.

CONCLUSIONS

Our results indicated that applying manure in combination with a N fertilizer resulted in lower leachate P concentrations and P and N loads in runoff than with manure alone. Applying N as either manure alone or manure plus AN showed no impact on leachate NO_3–N concentrations. Application of manure or manure plus AN increased Mehlich 1-P concentration in the Ap horizon than with treatments receiving no amendments. However, soil P accumulation of the treatments receiving manure plus AN was approximately 50% lower than those receiving manure application alone. Combining manure application with an inorganic N fertilizer represents an effective best management alternative that can reduce the risks associated with soil P and N buildup and subsequent losses to the environment.

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REFERENCES

Backhus, D.A., J.N. Ryan, D.M. Groher, J.K. MacFarlane, and P.M. Gschwend. 1993. Sampling colloids and colloid-associated contaminants in groundwater. Ground Water 31:466–479.

Burgoa, B., A.B. Bottcher, R.S. Mansell, and L.R. Allen, Jr. 1991. Distribution of residual soil phosphorus along transects for three dairies in Okeechobee County, Florida. Proc. Soil Crop Sci. Soc. Fla. 50:137–144.

Campbell, K.L., J.C. Capace, and T.K. Tremwel. 1995. Surface/Subsurface hydrology and phosphorus transport in the Kissimmee River basin, Florida. Ecol. Eng. 5:301–330.

Capece, J.C., K.L. Campbell, P.J. Bohlen, D.A. Graetz, and K.M. Portier. 2007. Soil phosphorus, cattle stocking rates, and water quality in subtropical pastures in Florida, USA. Rangeland Ecol. Manag. 60:19–30.

Dougherty, W.J., P.J. Nicholls, P.J. Milham, E.J. Havilah, and R.A. Lawrie. 2008. Phosphorus fertilizer and grazing management effects on phosphorus in runoff from dairy pastures. J. Environ. Qual. 37:417–428.

Eghball, B. 2002. Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. Agron. J. 94:128–135.

Eghball, B., D. Ginting, and J.E. Gilley. 2004. Residual effects of manure and compost applications on corn production and soil properties. Agron. J. 96:442–447.

Elliott, H.A., G.A. O'Connor, and S. Brinton. 2002. Phosphorus leaching from biosolids amended sandy soils. J. Environ. Qual. 31:681–689.

Evers, G.W. 2002. Ryegrass-bermudagrass production and nutrient uptake when combining nitrogen fertilizer with broiler litter. Agron. J. 94:905–910.

Fonyo, C., and E. Flaig. 1995. Phosphorus budgets for Lake Okeechobee tributary basins. Ecol. Eng. 5:209–227.

Hanrahan, L., W.E. Jokela, and J.R. Knapp. 2009. Dairy diet phosphorus and rainfall timing effects on runoff phosphorus from land-applied manure. J. Environ. Qual. 38:212–217.

Harmel, R.D., D.R. Smith, R.L. Haney, and M. Dozier. 2009. Nitrogen and phosphorus runoff from cropland and pasture fields fertilized with poultry litter. J. Soil Water Conserv. 64:400–412.

Kleinman, P.J.A., A.N. Sharpley, A.M. Wolf, D.B. Beegle, and P.A. Moore, Jr. 2002. Measuring water-extractable phosphorus in manure as an indicator of phosphorus in runoff. Soil Sci. Soc. Am. J. 66:2009–2015.

Mansell, R.S., S.A. Bloom, and P. Nkedi-Kizza. 1992. Experimental and simulated P transport in soil using a multireaction model. Soil Sci. 153:185–194.

Mansell, R.S., S.A. Bloom, and P. Nkedi-Kizza. 1995. Phosphorus transport in Spodosols impacted by dairy waste. Ecol. Eng. 5:261–279.

Mehlich, A. 1953. Determination of P, Ca, Mg, K, Na, NH_4. Soil Testing Div. Pub.1–53. North Carolina Dep. Agric., Raleigh.

Menjoulet, B.C., K.R. Brye, A.L. Pirani, B.E. Haggard, and E.E. Gbur. 2009. Runoff water quality from broiler litter-amended tall fescue in response to natural precipitation in the Ozark Highlands. J. Environ. Qual. 38:1005–1017.

Mulvaney, R.L. 1996. Nitrogen–inorganic forms.p.1123–1184. *In* D.L. Sparks et al. (ed.) Methods of soils analysis: Part 3. Chemical methods. SSSA Book Ser. 5. ASA and SSSA, Madison, WI.

Mylavarapu, R.S. 2002. UF/IFAS Extension Soil Testing Laboratory (ESTL) analytical procedures and training manure. Series in soil science. No. 1248. Florida Coop. Ext. Serv., Gainesville.

Mylavarapu, R.S., D. Wright, G. Kidder, and C.G. Chamblis. 2007. UF/IFAS Standardized fertilization recommendations for agronomic crops. Available at http://edis.ifas.ufl.edu/ss163 (verified 5 Aug. 2010). Florida Coop. Ext. Serv., Gainesville.

Nair, V.D., K.M. Portier, D.A. Graetz, and M.L. Walker. 2004. An environmental threshold for degree of phosphorus saturation in sandy soils. J. Environ. Qual. 33:107–113.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 539–579. *In* A.L. Page et al. (ed.) Methods of soil analysis: Part 2. 2nd ed. Agronomy Monogr. 9. ASA and SSSA, Madison, WI.

Obour, A.K., M.L. Silveira, M.B. Adjei, J.M. Vendramini, and J.E. Rechcigl. 2009. Cattle manure application strategies effects on bahiagrass yield, nutritive value, and phosphorus recovery. Agron. J. 101:1099–1107.

Rechcigl, J.E., G.G. Payne, A.B. Botcher, and P.S. Porter. 1992. Reduced phosphorus application on bahiagrass and water quality. Agron. J. 84:463–468.

SAS Institute. 1999. SAS/STAT guide for personal computers. Version 6. SAS Inst., Cary, NC.

Sharpley, A.N. 1997. Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter. J. Environ. Qual. 26:1127–1132.

Sharpley, A.N., P. Kleinman, and R.W. McDowell. 2001. Innovative management of agricultural phosphorus to protect soil and water resources. Commun. Soil Sci. Plant Anal. 32:1071–1100.

Sims, J.T., and D.C. Wolf. 1994. Poultry waste management: Agricultural and environmental issues. Adv. Agron. 52:1–83.

Soil Survey Staff. 1996. Keys to soil taxonomy. U.S. Gov. Print. Office, Washington, DC.

Toor, G.S., L.M. Condron, H.J. Di, K.C. Cameron, and B.J. Cade-Menun. 2003. Characterization of organic phosphorus in leachate from a grassland soil. Soil Biol. Biochem. 35:1317–1323.

USEPA. 1993. Methods for the determination of inorganic substances in environmental samples. USEPA 600/R-93/100. Method 353.2. USEPA, Washington, DC.

USEPA. 2002. National Water Quality Inventory. EPA 841-R-02–001. U.S. Environ. Protection Agency, Office of Water Quality, Washington, DC.

Villapando, R.R., and D.A. Graetz. 2001. Water table effects on phosphorus reactivity and mobility in a dairy manure-impacted spodosol. Ecol. Eng. 18:77–89.

Westerman, P.W., and M.R. Overcash. 1981. Short-term attenuation of runoff pollution potential for land-applied swine and poultry manure. p. 289–292. *In* Livestock waste: A renewable resource. Proc. 4th Int. Symp. on Livestock Wastes, Amarillo, TX. 15–17 Apr. 1980. ASAE, St. Joseph, MI.

Withers, P.J.A., S.D. Clay, and V.G. Breeze. 2001. Phosphorus transfer in runoff following application of fertilizer, manure, and sewage sludge. J. Environ. Qual. 30:180–188.